The Effect of USO Stability on One-Way Doppler Navigation of the Mars Reconnaissance Orbiter

Dolan E. Highsmith
Jet Propulsion Laboratory
4800 Oak Grove Drive
M/S 301-125L
Pasadena, CA 91109-8099
(V) 818-393-7855
(F) 818-393-6388
Dolan.E.Highsmith@jpl.nasa.gov

Condensed Abstract:

This paper provides a summary of a study to assess the effect of the stability of the ultra-stable oscillator (USO) on board MRO (Mars '05) on navigation accuracy when using one-way Doppler to the Deep Space Network. Subject to the assumptions of the covariance analysis, the results indicate that an oscillator with 10^{-12} short-term stability would provide navigation performance sufficient to meet the ephemeris requirements, but a 10^{-13} oscillator would ensure minimal loss of performance versus the nominal two-way Doppler.

Extended Abstract:

A key navigation capability of the Mars Reconnaissance Orbiter (MRO), the NASA mission to Mars to be launched in 2005, will be one-way Doppler transmission driven by the frequency from an ultra-stable oscillator (USO). The one-way Doppler navigation functionality becomes a critical asset in the 2007 to 2008 time frame when the Deep Space Network (DSN) will experience a veritable traffic jam of vehicles at Mars. To highlight, missions being launched to Mars in 2007 include the CNES orbiter and Netlanders, ASI/NASA Marconi orbiter, NASA Smart Lander, and possibly NASA Scout missions. MRO will still be in its primary mapping mission in '07, and Mars Odyssey ('01) and Mars Express ('03) could still be active in extended missions. Clearly, there will be a need during the '07-'08 time frame to maintain MRO mapping mission performance while sharing DSN uplink time. Given the likely dearth of two-way communications to MRO during this period of multiple spacecraft per aperture (MSPA) tracking, this study assesses the effect of the stability of the on-board USO on MRO navigation accuracy when using one-way Doppler tracking.

The covariance analysis approach uses ODP-heritage software to model the MRO mapping orbit (Table 1) and evaluate the effect of uncertainties (Table 2) on the MRO trajectory. Notable assumptions listed in Table 2 include angular momentum desaturations (AMD) and atmospheric drag. The AMD magnitude and frequency are designed to be much smaller than those experienced on MGS because AMDs are a driving orbit error source for that mission. The MRO mission will require a "quieter" spacecraft. Also, unlike previous missions in higher-altitude orbits, MRO will be significantly affected by atmospheric drag near its 253-km periapsis. The uncertainty in the drag acceleration is due to poorly known and potentially highly variable atmospheric density. For the purposes of this analysis, this uncertainty is accounted for in the drag coefficient term C_d. The resulting uncertainty in the drag acceleration is the same as if the uncertain parameter were density because the acceleration is formed by the equation

$$a_{drag} = \frac{1}{2}\rho V^2 C_d A/m$$

where ρ represents density. The 35% per rev stochastic noise on the drag accounts for the effect of a time-varying change in density between each periapsis pass.

The navigation performance is judged based upon the MRO ephemeris prediction and reconstruction requirements shown in Table 3. The tracking strategies compared in this analysis include two-way Doppler and one-way Doppler using oscillators with short-term stabilities (Allan deviations) of 10^{-13}, 10^{-12}, 10^{-11}, and 10^{-10}. The prediction analysis uses two days of DSN tracking to reach a converged orbit solution, and then formulates a one-week prediction. Two cases are examined for ephemeris prediction: with and without atmospheric drag. The results are shown in Figures 1-6, in which cases with and without drag are shown for radial, down-track, and cross-track directions. Each plot shows the 3σ error for tracking with two-way DSN and one-way DSN with the indicated on-board oscillator stabilities. These values are compared to the requirement which must be met at day 9 (two days of tracking plus a seven-day prediction).

Each plot also shows the tracking coverage by DSN stations 15 (Goldstone) and 45 (Canberra). The nominal DSN tracking schedule is assumed, comprising two eight-hour passes per day. Note, however, that this may be optimistic for the MSPA case. DSN downlink time may also become scarce in '07-'08, especially in the days and weeks leading up to critical events (e.g., Mars orbit insertion or entry, descent, and landing events). Thus, note that the results of this study are dependent on the amount of tracking available, and they would generally be worse with less tracking.

Earlier covariance analyses performed for MRO, including those used to identify the capability-driven navigation accuracy requirements in Table 3, did not include the effect of drag. In fact, two-way DSN values similar to those in Figures 1, 3, and 5 were used to define the prediction requirements (with added margin). Comparison of these cases to the ones with drag shows that drag dominates the radial and along-track (i.e., in-plane) orbit prediction errors, but has no noticeable effect in the cross-track direction. However, it is the cross-track direction that drives the choice of oscillator for prediction from one-way tracking. Figures 2 (radial) and 4 (down-track) show that all but the 10^{-10} case meet the respective requirements at day 9, though with little or no margin. Figure 6 (cross-track) shows that neither the 10^{-10} nor the 10^{-11} case meets the cross-track requirement.

Therefore, the ephemeris prediction requirements are met in all three directions by the two-way and one-way with 10^{-13} and 10^{-12} oscillator stabilities. Further examination of the figures reveals that one-way tracking with the 10^{-13} oscillator provides similar performance to the nominal two-way. With a two-day orbit fit prior to prediction, one-way tracking with the 10^{-12} oscillator meets the requirements within the margins for two-way performance. Note, however, that if only one day (or 16 hours) of tracking is available, then the accuracy of the initial ephemeris used for prediction would be worse in the one-way cases. As a consequence, the cross-track error shown in Figure 6 for the 10^{-12} case, for example, could potentially violate the one-week prediction requirement.

Maintaining the assumption of nominal tracking coverage, the fact remains that the 10^{-11} one-way case fails only in the cross-track direction. One may ask whether the MRO mission could still be accomplished during periods of one-way tracking using a 10^{-11} oscillator. To do so, the cross-track prediction error allowed must be at least 300 meters to account for the value reached by the 10^{-11} curve in Figure 6. However, the desired total cross-track mapping error, which includes multiple sources of error besides orbital position, is *less than* 300 meters. A cross-track position error of 300 meters would allow room for neither the error due to roll attitude nor for sufficient margin below 300 meters. Therefore, based upon the desired mapping error, the MRO mission could not be accomplished successfully with one-way tracking using a 10^{-11} oscillator.

The ephemeris reconstruction analysis reaches similar conclusions in terms of the stability of oscillator required to meet the reconstruction requirements in Table 3. That is, two-way and one-way with 10^{-13} and 10^{-12} oscillators meet the reconstruction requirements in all three directions, and the 10^{-11} results fail in the cross-track direction.

Subject to the assumptions of the covariance analysis, the results indicate that an oscillator with 10^{-11} short-term stability would not meet the cross-track navigation requirement and would not allow the desired 300 meter total cross-track mapping error. An oscillator with 10^{-12} stability would provide navigation performance sufficient to meet the ephemeris requirements, but a 10^{-13} oscillator would ensure minimal loss of performance versus the nominal two-way Doppler.

Table 1: MRO orbit parameters

a = 3734.375 km	ω = 358.094 deg
e = 0.02256	Ω = 26.845 deg
i = 92.87 deg	$T-T_n$ = 0.0 sec
T_i = 26-SEP-2006 01:50:13.0 UTC	
T_f = 05-OCT-2006 01:50:13.0 UTC	
S/C Mass = 1000 kg	
S/C Area = 17 m^2	
Atmosphere = MarsGRAM 2000	

Table 2: Covariance analysis a priori assumptions.

Quantity	**Uncertainty**
Position	10 km
Velocity	1 m/s
Angular Momentum Desat (AMD)	0.1 mm/s every 48 hr
Atmospheric Drag (C_d)	100% init., 35% per rev stochastic
Gravity	Subset of MGS 75d Field
Solar Coefficient	10%
UT1-UTC	0.35 ms
X & Y Pole Motion	15 nrad
Wet Troposphere (zenith)	2 cm
Dry Troposphere (zenith)	2 cm
Ionosphere (zenith)	0.278 x 10^{17} elec/m^2
DSN Station, Dist. Spin Axis	10 cm
DSN Station, Longitude	16 nrad
DSN Station, Z	10 cm
Planetary Ephemeris (Set III)	8.8e-10
GM	0.008581 km^3/s^2
Outgassing	1e-13 km/s^2

Table 3: MRO ephemeris requirements.

	Radial (km)	Downtrack (km)	Crosstrack (km)
7 Day Prediction	0.04	1.50	0.05
Reconstruction	0.01	0.30	0.04

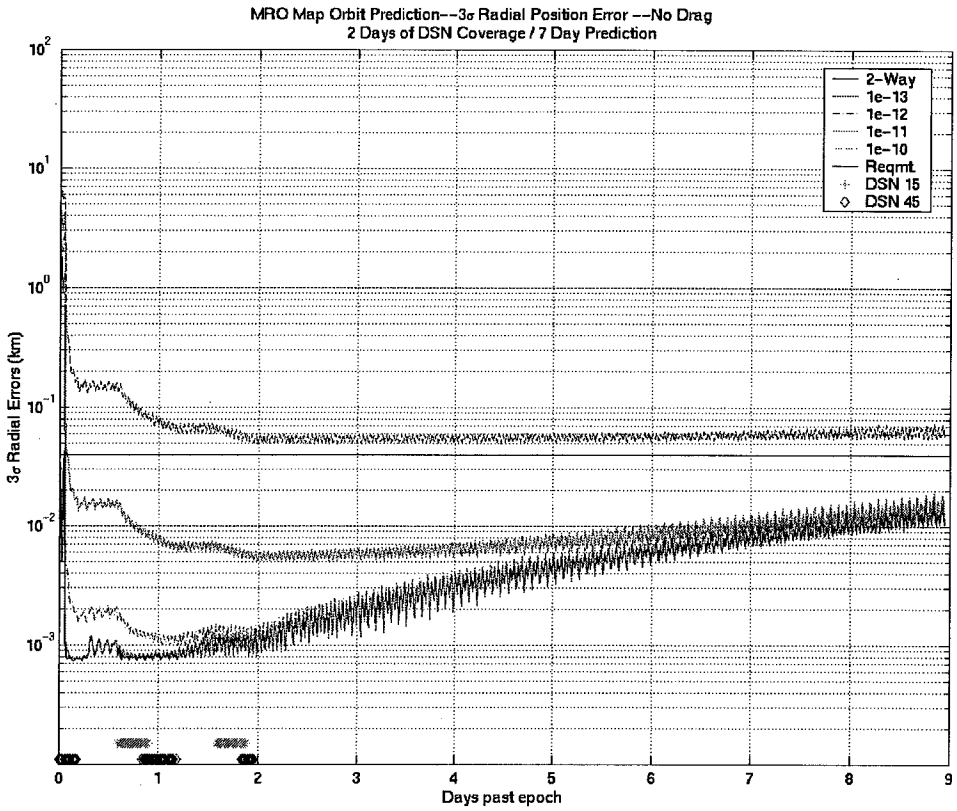
MRO Map Orbit Prediction--3σ Radial Position Error --No Drag
2 Days of DSN Coverage / 7 Day Prediction
2-Way
1e-13
1e-12
1e-11
1e-10
Reqmt
DSN 15
DSN 45
3σ Radial Errors (km)
Days past epoch

Figure 1

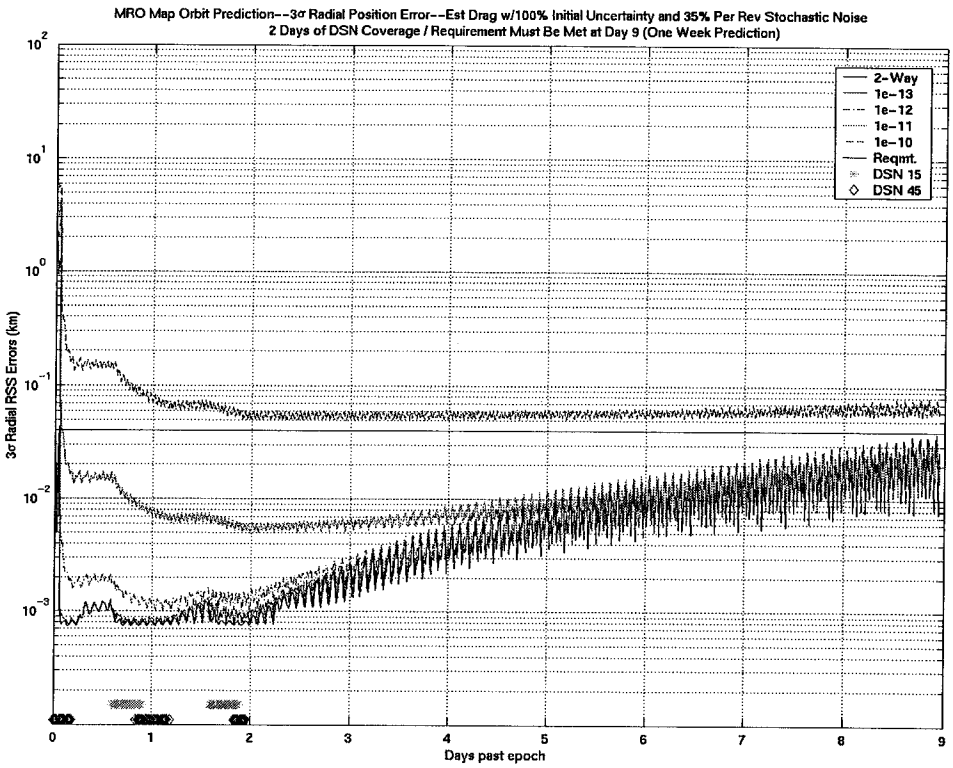
MRO Map Orbit Prediction--3σ Radial Position Error--Est Drag w/100% Initial Uncertainty and 35% Per Rev Stochastic Noise
2 Days of DSN Coverage / Requirement Must Be Met at Day 9 (One Week Prediction)
2-Way
1e-13
1e-12
1e-11
1e-10
Reqmt.
DSN 15
DSN 45
3σ Radial RSS Errors (km)
Days past epoch

Figure 2

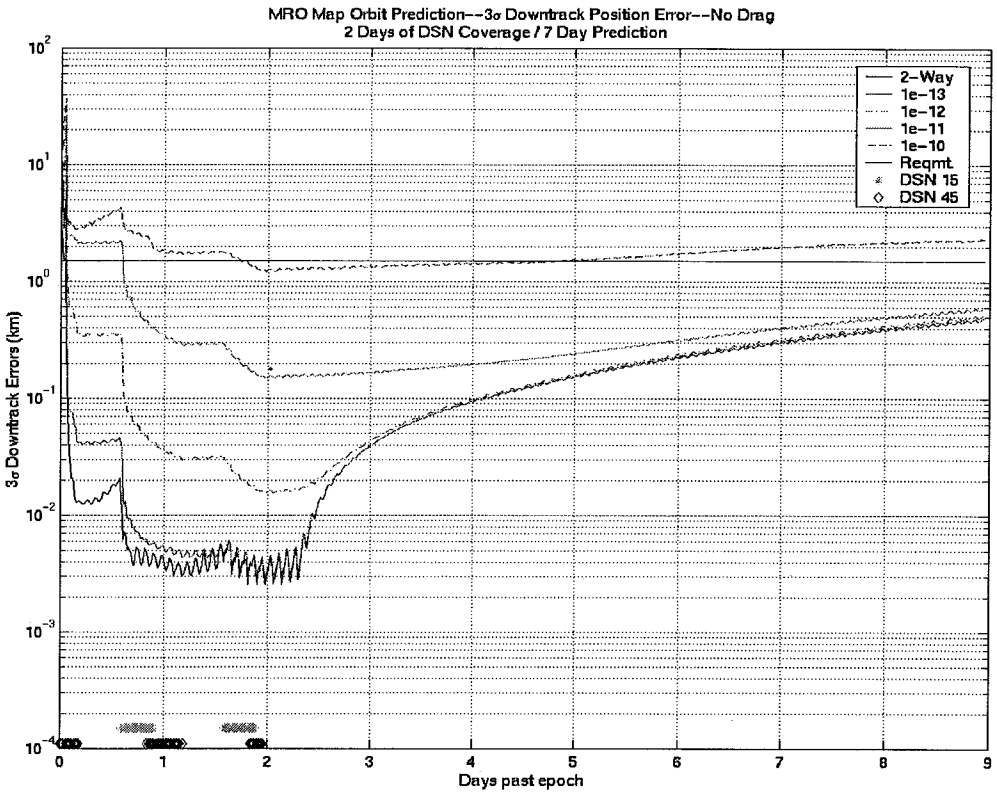
MRO Map Orbit Prediction--3σ Downtrack Position Error--No Drag
2 Days of DSN Coverage / 7 Day Prediction
3σ Downtrack Errors (km)
Days past epoch
2-Way
1e-13
1e-12
1e-11
1e-10
Reqmt
DSN 15
DSN 45

Figure 3

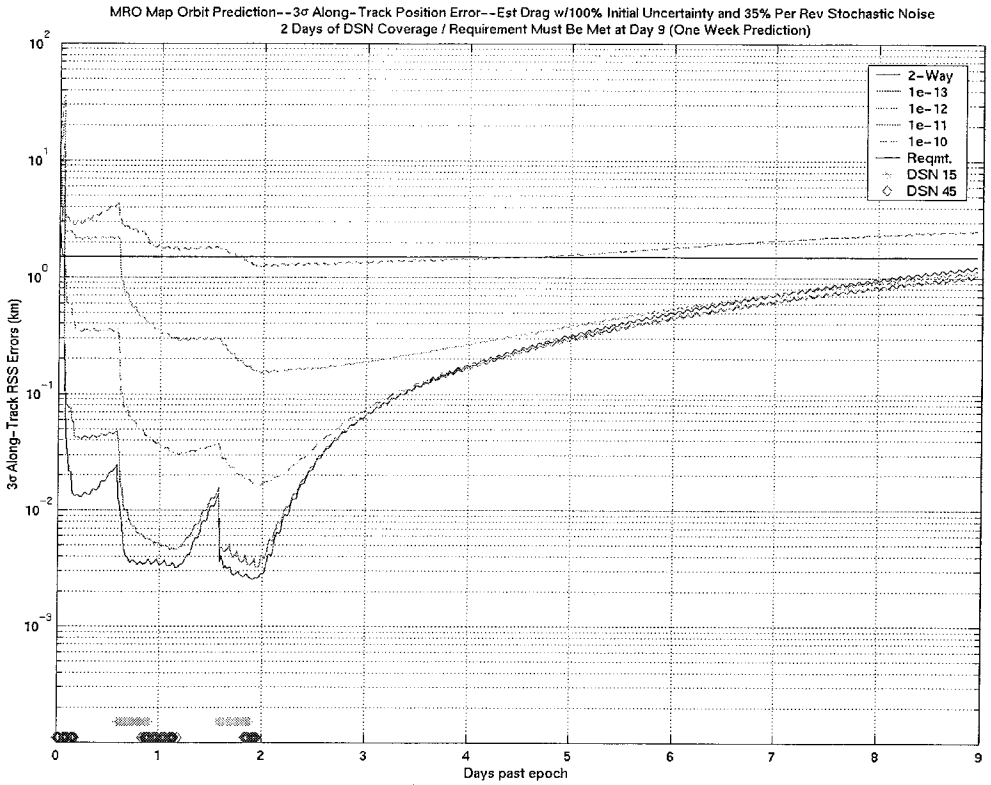
MRO Map Orbit Prediction--3σ Along-Track Position Error--Est Drag w/100% Initial Uncertainty and 35% Per Rev Stochastic Noise
2 Days of DSN Coverage / Requirement Must Be Met at Day 9 (One Week Prediction)
2-Way
1e-13
1e-12
1e-11
1e-10
Reqmt.
DSN 15
DSN 45
3σ Along-Track RSS Errors (km)
Days past epoch

Figure 4

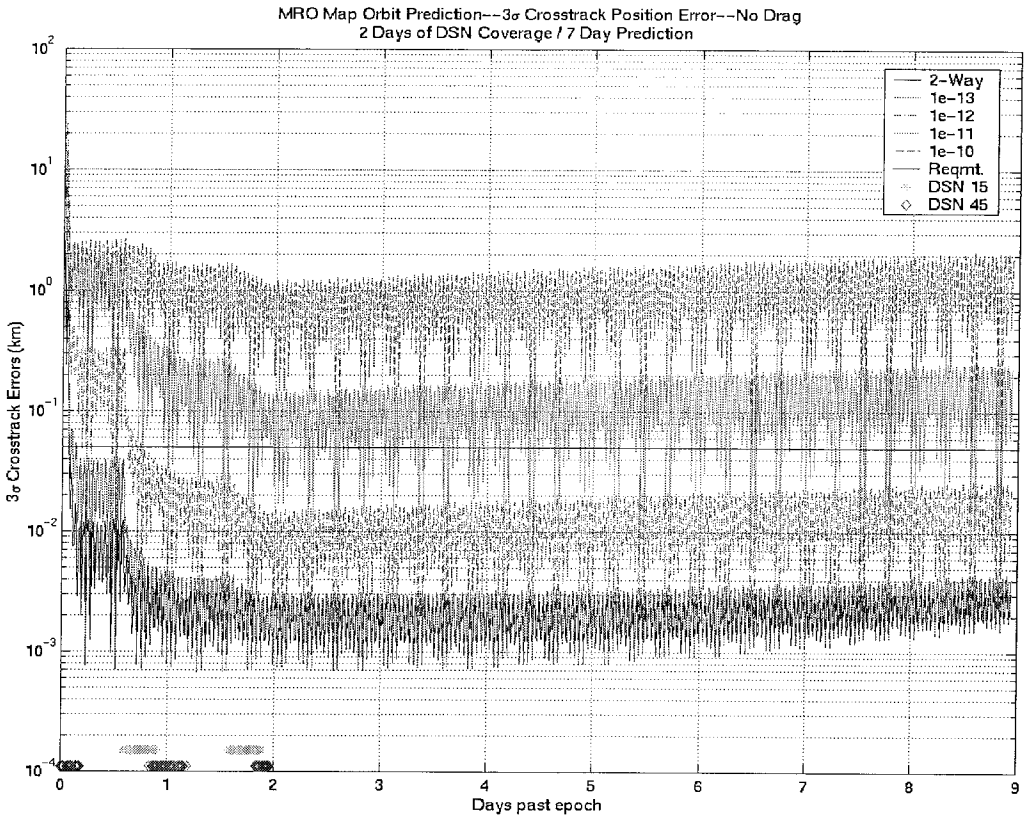
MRO Map Orbit Prediction--3σ Crosstrack Position Error--No Drag
2 Days of DSN Coverage / 7 Day Prediction
2-Way
1e-13
1e-12
1e-11
1e-10
Reqmt.
DSN 15
DSN 45
3σ Crosstrack Errors (km)
Days past epoch

Figure 5

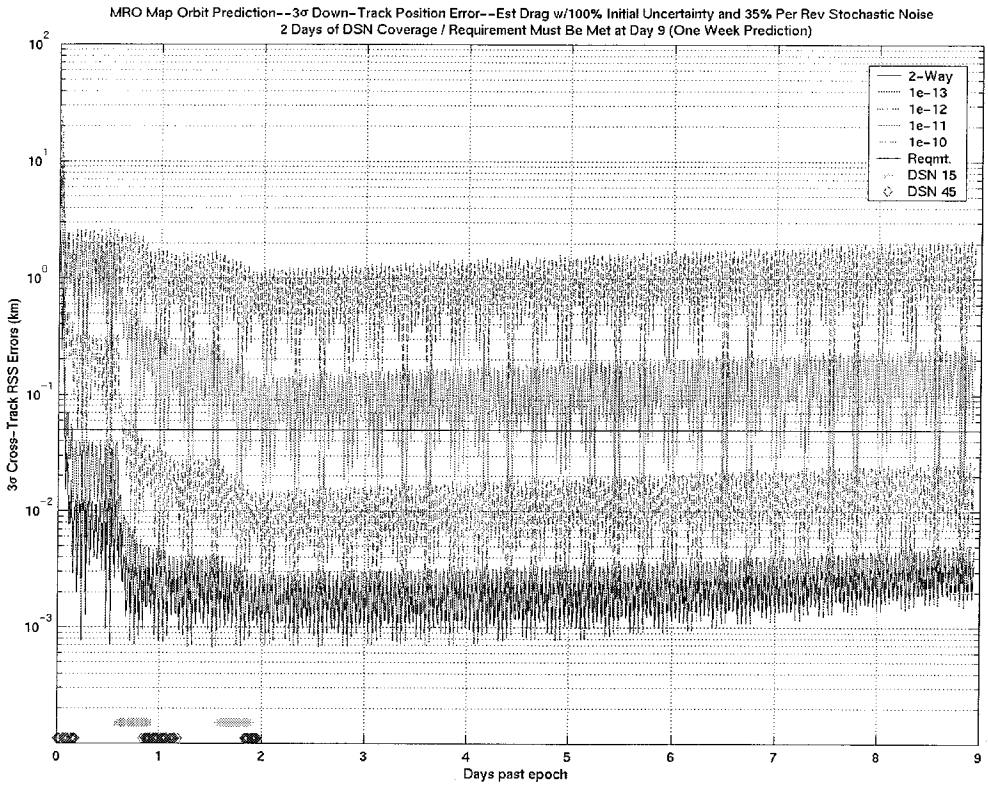
MRO Map Orbit Prediction--3σ Down-Track Position Error--Est Drag w/100% Initial Uncertainty and 35% Per Rev Stochastic Noise
2 Days of DSN Coverage / Requirement Must Be Met at Day 9 (One Week Prediction)
2-Way
1e-13
1e-12
1e-11
1e-10
Reqmt.
DSN 15
DSN 45
3σ Cross-Track RSS Errors (km)
Days past epoch

Figure 6